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(54) LINEAR ELECTRIC MOTORS

(71) We, INFORMATION MAGNETICS CORPORATION, a Corporation organized and existing under the laws of the State of California, United States of America, of 795 South Kellogg, Goleta, California, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to linear electric motors that produce reciprocating motion and has particular reference to linear motors employing tubular magnets.

While there are numerous uses for linear electric motors, the present invention will be described with reference to linear motors for use in moving read-write heads for reading and imprinting magnetic signals on the magnetizable surfaces of rotatable disks. Such disks are commonly used for the retention and recovery of data for computers. The requirements for such motors give rise to important dynamic electrical characteristics as well as static or steady state conditions.

Linear electric motors heretofore used on disk drives have been of the open-end type and have projected a very strong stray magnetic field from this open end. This field has been so intensive that it interfered with the read-write heads and their associated circuits. Efforts to reduce this stray field have been directed toward enclosing the working air gap with a casing of soft iron or similar magnetic material, that is to do away with the open-end type of construction.

We have discovered, however, that open-end motors can be satisfactorily utilized if the magnetic field has a radial orientation. If readily oriented magnets are used in open-end motors, this stray field can be reduced to negligible flux densities. In comparing an open-end motor of our design with a conventional open-end motor, we have found that our motor has a field strength of 3 gauss at 4 inches and the conventional equivalent motor 30 gauss at the same distance. Apparently this large stray field of conventional motors is due to having the magnet axis aligned with the motor axis, and this field is projected out through the air gap and from the open end of the motor.

A linear electric motor according to one aspect of our invention comprises a tubular shell of magnetic material having a tubular axis; a central core of magnetic material magnetically connected to the shell by at least one low reluctance magnetic path; a tubular magnet disposed inside of the shell and having a radial polarization and defining an air gap with either the shell or the central core; a movable armature coil disposed in the air gap and having conductors generally in planes transverse to the tubular axis of the shell; means for supplying electric current to the armature coil; and means connected to the armature coil and extending to the exterior of the motor for transmitting the motion of the armaure coil.

A linear electric motor according to another aspect of our invention comprises a hollow cylindrical magnet having opposite poles on the interior and exterior surfaces of the cylinder and having a cylindrical axis; means for concentrating the lines of flux located on the interior surface of the magnet; a generally cylindrical pole piece spaced from the inside surface of the magnet to define a working air gap; a magnetic return circuit connecting the pole piece to the other surface of the cylindrical magnet including a low reluctance shell enclosing the magnet and the air gap; a coil disposed in the air gap for axial movement and constructed such that current can flow in it in a plane transverse to the cylinder axis; and means extending through the magnetic return circuit to mechanically transmit the motion of the coil as it moves axially within the cylindrical magnet.

By way of example linear motors in accordance with the invention will now be described with reference to the accompanying drawings in which:—

Fig. 1 is a three dimensional view of

one such motor with a portion broken away to show the interior construction;

Fig. 2 is a schematic view in elevation with parts in full section, showing a carriage for supporting the armature coil of Fig. 1 in cantilever fashion;

Fig. 3 is a fragmentary cross-sectional view through a portion of a self-supporting armature coil useful in connection with the motor of Fig. 1;

Fig. 4 is a fragmentary sectional view through a second construction for a self-supporting armature coil having several layers of conductor;

Fig. 5 is a view of a modified form of central core for the motor of Fig. 1, showing an end view;

Fig. 6 is a sectional view through another such motor, showing the compensation coils on the interior of the magnet, rather than on the exterior of the central core, as in Fig. 1;

Fig. 7 is a sectional view through a production version of the motor of Fig. 1;

Fig. 8 is a schematic diagram of the relationship between the armature coil and the compensation coils of the production motor of Fig. 7;

Fig. 9 is a three-dimensional schematic view of a modified form of single shortened turn compensation for a motor of Fig. 1 or Fig. 7;

Fig. 10 is a modified form of circuit, showing the compensation coil in parallel with the armature coil;

Fig. 11 is a modified circuit, showing the armature coil in series with the compensation coil;

Fig. 12 is a sectional view through another such motor wherein compensation windings are disposed in grooves in the central core;

Fig. 13 is a sectional view through another such motor wherein the compensation winding is concentrated at one point on the central core;

Fig. 14 is a three-dimensional view of yet another such motor wherein the air gap is enclosed at both ends to further reduce stray flux;

Fig. 15 is a diagrammatic sectional view through the motor of Fig. 14 showing the distribution of the lines of flux;

Fig. 16 is a sectional view through another such motor wherein the armature coil is supported by radial fins secured to an axial reciprocating rod.

Referring to Fig. 1, the linear motor designated 10 rests on a surface 11. Brackets 12 support a cylindrical shell 13 which is open at its right end, but closed at its left end by a plate 14. Supported in cantilever fashion from the end plate 14 is a central core 16 which is spaced from and concentric with the outer shell 13. The shell 13, the end plate 14 and the central core 16 are all formed of magnetic material; that is, material of high magnetic permeability and low magnetic reluctance, such as soft iron and low-carbon steel.

Disposed on the interior of the outer shell 13 is a tubular magnet 17 which is radially polarized uniformly over its entire cross-section and length. Accordingly, the notations on the right end of Fig. 1 of "N" and "S" illustrate that one pole is toward the interior surface of the tubular magnet 17 and the other pole is on the exterior surface. Lines of flux from this magnet travel into the outer shell 13, thence to the left to the end plate 14 and into the central core 16 to become fairly uniformly distributed over the entire inner surface of the magnet 17. The inner surface of the magnet 17 is spaced from the central core 16 to define an air gap 18 which is the working air gap of the motor. A cylindrical armature coil 19 is disposed in this air gap 18 and cuts the lines of flux between the central core 16 and the interior surface of the magnet 17.

Illustrated in Fig. 2 is a presently preferred method of supporting the armature coil 19 and this includes a carriage 21 having wheels 22 which support it on accurately machined rails 23. Fastened to the top of the carriage 21 is a tubular member 24 formed of a non-conductor material, such as plastic, and this may be secured in any suitable fashion to the carriage 21, such as by fasteners 26. The left end of the tube 24 of Fig. 2 may be adhered to the armature coil 19 in any suitable fashion, as by the use of epoxy cement. The carriage 21 accurately positions the armature coil 19 within its air gap, so that extremely close tolerances may be maintained in spacing between the adjacent surfaces defining the air gap 18.

Referring back to Fig. 1, current may be supplied to the armature coil 19 in any suitable fashion, preferably from the side of the coil, although it could be supplied through the carriage 21. It will be noted that the exterior shell 13 of magnetic material is slotted lengthwise at 28 and the tubular magnet 17 has a similar slot 29 in registry with the shell slots 28. Extending from the shell 13 is an L-shaped member 31 which supports a pair of electrical terminals 32 to which are connected a pair of flexible strip conductors 33, the other ends of which are connected to a lengthwise twin conductor strip 34 on the armature coil 19. The strip 34 carries current from one conductor 33 to one end of the armature coil 19 and receives current from the other end of the coil 19. If desired, a centre insulator strip 36 may be disposed between the two conductors 33.

Provided on the exterior of the central core 16 is a compensation winding 37. This winding creates a magnetic flux which is

opposite to and approximately equal to the magnetic flux induced by the current through the armature coil 19. Various circuits may be employed for creating a current in this compensation coil 37, as illustrated more fully hereafter in Figs. 8 to 11. The essential requirement is that the part of the compensation coil, or all of it, as the case may be, that is generating a counter flux to that of the armature coil, has an effective number of ampere turns approximately equal to that of the ampere turns of the armature coil. The compensation coil corrects for the distortion of the lines of flux from the magnet 17 to the central core 16. When armature coil 19 is energized, it creates a magnetic field of its own, which is at right angles to the generally radial lines of flux from the central core 16 to the magnet 17. This tends to push these lines of flux to one or other end of the magnet 17, depending upon the direction of current in the coil 19. The coil 19, accordingly, cuts fewer lines of flux and has less force than would otherwise be the case. The compensation winding 37 produces a counter flux to that generated by the armature coil, and this restores the flux density pattern to approximately that which exists in the absence of energizing the armature coil. The force, therefore, produced by the armature coil does not fall off at high current densities for the armature coil, which is a common characteristic of linear motors in the absence of compensation.

PRODUCTION VERSION OF MOTOR

Referring to Fig. 7, there is illustrated the geometry of a presently preferred production motor which embodies the design of Fig. 1. The various parts therein will be referred to by the same reference numerals as in Fig. 1.

The outer shell 13 is recessed at the left end at 15 to receive a plurality of washers which act as the end plate 14, and the central core 16 is also recessed at 20 to receive these washers. The tubular magnet 17 fits tightly within the outer shell 13 for good magnetic connection. The central core 16 may be centrally bored at 16*a* and the right end of this bore may receive a bushing 16*b*. The compensation winding 37 is tightly wound on the exterior of the central core 16 and the armature coil 19 is very closely spaced away from the outer surface of the compensation winding 17 and the interior surface of the magnet 17.

SELF-SUPPORTING ARMATURE COILS

Illustrated in Figs. 3 and 4 are two presently preferred forms of self-supporting armature coil. It will be noted from Fig. 2 that the armature coil 19 is end supported and the maximum utilization of air gap requires that there be as close a spacing as possible between the turns of the coil and the effective width of the air gap. Accordingly, internal or external supporting structures are undesirable in these armature coils. In Fig. 3 there is illustrated a single layer self-supporting armature coil formed of flat aluminuim wire 41 which is edge wound in the form of a helix and only a small length of this helix is sectioned in Fig. 3. The wire 41 is insulated by electrically forming an oxide on the surface, which wire is then referred to as anodized aluminium. This layer of oxide on the surface is indicated at 42. Prior to winding the anodized aluminium into the helical coil it is coated with a thin layer of thermo-setting plastics and this plastics is partially dried so that it will remain on the wire during the forming of the helix. This coating of plastics is indicated by the reference numeral 43. The wound helix is then compressed endwise and subjected to heat at a curing temperature so that the plastics is intimately bonded to the anodized surface which is extremely adherent to the aluminium on which it is formed. Thermo-setting spoxy resins have been found to be very useful for this purpose, although, undoubtedly, other thermo setting plastics may be equally successful, such as the phenolics.

Illustrated in Fig. 4 is a form of self-supporting coil which is useful if copper wire is used. Plastics adhere very poorly to the smooth surface of drawn copper wire and, accordingly, a matrix construction is more satisfactory than the single turn of Fig. 3. Flat copper wire 46 has its small edges abutting and is wound into an interior helix. Prior to winding, the wire is coated with a suitable resin, such as a thermo-setting resin, and this is dried sufficiently so that it will not come off during the winding of the helix. A second layer of flat copper wire 47 is also wound into a helix, but is wound in an overlapping relationship to the flat wire 46. When the two helices are completely wound, they are then cured with or without pressure. The result is a matrix, as shown in exaggerated from in Fig. 4, wherein plastics 48 surrounds each turn of a wire and is disposed between the two helices of wire 46 and 47. The result is a matrix or a network of plastics around the wire turns which firmly holds them into relationship. The physical strength of the flat copper in overlapping relationship adds extreme rigidity and strength to this arrangement. The current is introduced into each wire 46 and 47 of the respective helices in parallel, as illustrated by the plus and minus signs and the leads 49 therefrom. If pressure is used, radial pressure is preferable to endwise pressure. The copper has less resistance than aluminium and where this is a factor,

the copper construction of Fig. 4 may be used.

MODIFIED CENTRAL CORE

Illustrated in Fig. 5 is an end view of a central core 16*c* which is formed of a number of square bars or steel or soft iron 51 which are suitably held together, as by epoxy cement. When the epoxy is completely set up, the entire bar is ground or otherwise given a circular external shape or any shape desired according to the cross-section of the electric motor.

MODIFIED COMPENSATION COIL

Illustrated in Fig. 6 is a cross-section of a round linear motor wherein the compensation coil is disposed on the interior of the tubular magnet, rather than on the exterior of the central core. Accordingly, the motor 50 has an exterior shell 52 of magnetic material inside of which is disposed a tubular magnet 53. Disposed tightly in contact with the interior of the tubular magnet 53 is the compensation coil or winding 54. Disposed inside of this compensation coil 54 is an axially movable armature coil 56 supported by a plurality of radial vanes 57 extending from a central rod 58 and these are disposed in slots 59 in a central core 60. Such a construction makes necessary an external carriage as is illustrated in Fig. 2. The operation of the modification of Fig. 6 is similar to that of Fig. 1.

COMPENSATION CIRCUITS

Shown in Figs. 8 through 11 are compensation circuits that are illustrative of the type of relationships that can be established between the armature coils and the compensation windings. Shown in Fig. 8 is a short-circuited type of compensation coil 37. This is presently preferred for the motor of Fig. 7 and the desired short circuit condition may be obtained by grounding each end as well as the centre (or other intermediate points) to the metal core 16. Any other suitable ground is useful. Illustrated in Fig. 9 is a tubular conductor 61 which is slipped tightly over the central core 16. In both Fig. 8 and Fig. 9 the armature coil 19 creates a flux in the associated compensation winding 37 or the tube 61 with every change of current in the armature coil 19. This induces a current in the shorted coil 37 or in the tube 61 which can be considered as a single turn coil. The magnetic field created by the current flow through the armature coil 19 is designated by an arrow 62 and the induced current in the compensation coil creates an opposite and approximately equal flux designated by the arrow 63. These shorted turns of Figs. 8 and 9 have the advantage of having the compensation currents axially co-extensive with the armature coil regardless of where the armature coil might be located over its path of travel along the central core.

Illustrated in Fig. 10 is a circuit wherein an armature coil 19*a* is connected in parallel with a compensation coil 37*a*. The connections are such that the current flows through the coils are opposite, creating equal and opposite fluxes indicated by the appropriate arrows. In this case, the compensation coil 37*a* must be wound the full length of the travel of the armature coil and parts of the compensation coil are energized which are not fully effective because the compensation coil has a greater axial length than the axial length of the armature coil 19*a*.

Illustrated in Fig. 11 is a circuit wherein an armature coil 19*b* is connected in series with a compensation coil 37*b*. Here also, the currents are in opposite directions, producing fluxes which are opposing each other, as indicated by the arrows, and the ampere turns of each of the two windings are selected so that they are approximately equal. However, the ampere turns of the compensation coils of Figs. 10 and 11 may have to be greater than that of the armature coils because of their more extensive axial length.

It will be appreciated that the compensation circuits of Figs. 8 and 9 primarily accommodate dynamic, i.e. extremely rapid, operation of the motor, whereas the compenation circuits of Figs. 10 and 11 accommodate static, i.e. slow, operation. The extreme rapidity of movement required for the read-write heads of data disks gives rise to a high frequency, which can be as high as 500 cycles per second. In this case, the dynamic compensation is of more importance than the static, and the compensating fluxes ebb and flow according to the changes of current in the armature. In Figs. 10 and 11, the counteracting forces are equal to that of the current flow in the armature regardless of the rate of movement. These accommodate, of course, dynamic modes of operation as well as static operation.

OPERATION OF FIGS. 1, 2 AND 7

The output of the motors of Figs. 1 and 7 is transmitted by the movable armature coil 19 to the plastics tube 24 which, in turn, moves the carriage 21 to which the devices are connected that are desired to be moved. The output of the motors, accordingly, is a rectilinear movement.

The tubular permanent magnet 17 creates a steady flux between its interior surface and the central core 16 of magnetic material. Referring to Fig. 1, current is passed from the terminals 32 through the strips 33 to each end of the armature coil 19 to cause it to move in one direction or the other, depending upon the direction of current flow. The carriage 21 of Fig. 2 supports the coil

19 in its very close spaced relationship to the interior of the magnet. The reaction between the armature and flux extending from the core to the magnet causes the flux to be moved to one end of the armature coil or the other, depending on the direction of current flow. The function of the compensation winding 37 is to reduce this distortion so that the armature coil is operating against a steady flux density throughout its length. Changes of current in the armature coil induce currents to flow in the shorted turns (Fig. 8) of compensation coil 37 and it, in turn, sets up a magnetic flux 63 which is opposite and approximately equal to the magnetic flux 62 of the armature coil. The distortion of the radial lines of flux between the central core 16 and the tubular magnet 17 is, accordingly, eliminated without any decrease in the axial force generated by current in the armature coil 19.

Referring to Fig. 7, it will be noted that the axial length of the armature coil 19 is approximately half of the axial length of the magnet 17. The travel of the armature coil is preferably limited between positions in which the right end of the armature coil is within the right end of the magnet 17 and the left end of the armature coil 19 is within the left end of the magnet 17. Slight overruns can, of course, be used without appreciable reduction in the force developed. The orientation of the magnetic fields of Figs. 1 and 7 is radial, as indicated by the letters "N" and "S" shown in the respective drawings.

MODIFIED MOTOR OF FIG. 12

Illustrated in Fig. 12 is a modified form of the motor of Fig. 7 wherein a central core 200 is secured by washers 201 to an outer shell 202. Within the shell 202 is closely fitted a tubular magnet 203 having radial polarization. A working air gap 204 is formed between the interior of the magnet and the central core 200.

It has been discovered that grooves can be cut in the exterior of the core without reducing the magnetic dimension in a radial direction. That is, the grooved central core gives as strong a flux in the working air gap as a smooth one. Compensation coils can be placed in these grooves without occupying any part of the air gap.

Accordingly, a helical groove 205 is formed in the exterior surface or periphery and a compensation winding is disposed therein that gives as good compensation as though on the surface as in Fig. 7. An armature coil (not shown) can be placed in the air gap 204 as in Fig. 7.

These grooves can be ring-shaped for short circuited turns.

MODIFIED MOTOR OF FIG 13

Illustrated in Fig. 13 is a motor wherein the compensation coil does not occupy the air gap. The armature of the motor is not shown in Fig. 21, and the same type of armature can be used as that illustrated in Figs. 1, 2 and 7. An exterior shell 225 of magnetic material such as soft iron surrounds a tubular magnet 226 that is radially polarized, and a central core 227 is coaxially positioned with respect to the tubular magnet 226 by a plurality of washers 228. The axial extent of the magnet 226 is less than the distance from the washers 228 to the right end, leaving a space 229. Wrapped around the central core 227 at the region of the space 229 is a compensation coil 330, which is preferably connected in parallel or series with the armature coil (not shown). The compensation coil 330 may also consist of a shorted coil or shorted turns in a coil. The central core 227 may be laminated.

In operation, the armature coil will create a flux in the central core 227 and the compensation coil 330 generates an opposing flux, thus largely isolating the permanent magnet 226 from the flux surges due to current in the armature coil, and reducing the displacement of the flux lines in the air gap.

For manufacturing economy it is cheaper to make the tubular magnets of longitudinal cylindrical segments, for example, three sections of 120° arc. Also the outer shells of Figs. 12 and 13 are inexpensively manufactured from concentric laminations preferably rolled from sheet steel or iron. Laminations are added toward the left where the total flux in the shell is greater.

CLOSED MOTORS OF FIGS. 14—16

Illustrated in Figs. 14 through 16 are tubular magnet motors that have fully enclosed air gaps to reduce stray flux to a minimum. These motors are preferably compensated in the same manner as the open-end motors. They also are constructed with one surface of the air gap formed by the tubular magnet and a continuous core member (outer shell or inner core) forming the other surface of the air gap to obtain an air gap of uniform thickness for the full length of the magnet. Illustrated is a modification that concentrates the flux for peak performance, but with more expensive construction.

Referring to Fig. 14 there is illustrated another linear motor 310 embodying the invention. Disposed on the interior of the motor is a tubular magnet 311 which has an axis 312. Disposed on the interior cylindrical surface of the magnet 311 is a soft iron sleeve 313 which concentrates the lines of flux emanating from the cylindrical surface. Spaced from the inner surface of the sleeve 313 is a ring 314 of soft iron or other low reluctance material and the spac-

ing forms an air gap 316 which is the working air gap of the motor. Disposed in the air gap 316 is a coil 317 through which current may pass to interact with the flux present between the ring 314 and the sleeve 313. It is this interaction of current in coil 317 and the magnetic flux that causes the coil to move and thereby give rise to the linear motion for which the motor is designed.

The motor may be supported in any suitable manner, and we prefer at present to employ a plurality of mechanical tubes 318 which not only support the motor but also act as a guide for the output motion of the motor. The tubes 318 pass through a pair of end plates 319 and 321, preferably of soft iron, and these end plates 319 and 321 support the motor. Passing through holes in the end plates 319 and 321 is a bar 322 of soft iron in intimate contact with the interior cylindrical surface of the soft iron ring 314. On the inside of each end plate 319 and 321 is a washer slug 323 forming part of the magnetic return circuit and the interior and exterior diameters of the slugs 323 are in intimate cantact with the bar 322 and an exterior shell 324 which completely surrounds the magnet 311, the soft iron sleeve 313, and air gap 316.

We prefer at present to employ air bearings to guide the motion of the coil 317, although any suitable bearings could be employed. Cut into the top and bottom of the exterior shell 324, tubular magnet 311 and sleeve 313, are slots 326 through which pass struts 327 mechanically connected at their inner ends to the coil 317 and the outer ends of which have air bearing bushes 328 riding on the exterior of the support tubes 318. A pair of bridge members 329 may connect the strut bearings 328 to a corresponding pair of air bearings 331 connected by a single diametric strut 332 to which may be connected the mechanical parts to be moved by the motor 310. Arrows 333 and 334 indicate the motion of this strut 332. The air bearings are supplied by air under pressure delivered through tubes 336. The struts 327 may also carry the electric current to the coil 317 and there is illustrated a two wire conductor 337 leading to the lower air bushing 328 and this conductor is connected to the coil 317.

The materials of construction are important in the operating characteristics of the motor. Soft iron has a capability of transmitting several times the flux density of the strongest permanent magents, and four or five times the flux density of ceramic magnets. This is the reason, therefore, for putting the bushing 313 of soft iron on the interior of the cylindrical magnet 311. This bushing or sleeve gathers up the lines of flux from the entire axial length of the magnet 311 to concentrate this flux in the region of the ring 314. The ring 314 is likewise preferably formed of soft iron or similar low magnetic reluctance material. The ring 314 is in intimate contact with the exterior surface of bar 322, which also may be formed of soft iron.

Referring to Fig. 15 there is illustrated the magnetic circuit of the motor of Fig. 14. It will be noted that the tubular magnet 311 has the iron bar 322 passing through it and has the sleeve 313 disposed on its interior surface. The air gap 316 is formed between the interior surface of the sleeve 313 and the ring 314. The lines of force are indicated schematically by several continuous lines passing through the magnet and the air gap. It will be noted that the sleeve 313 gathers up the lines of flux from the entire surface of the cylinder 11 and concentrates them at the air gap 316. The magnet 311, in trying to form lines of flux between its north pole and south pole, is provided with a path of least resistance or lowest reluctance through the soft iron structure 313, 314, 324, 323 and 322, forming a low reluctance circuit which the lines of flux follow instead of trying to circuit back within the magnet itself, or through the air gap at each end. In this connection, the magnet 311 is spaced an appreciable distance from the end slugs 323 and this spacing is indicated by the arrows 315. The return circuit, therefore, for the lines of flux of the magnet 311 is through the sleeve 313, through the air gaps 316, through the pole piece ring 314, through the central bar 322, through the end slugs 323 and through the exterior shell 324, to the exterior of the cylindrical magnet 311. It will be appreciated that the air gap 316 is made as small as possible consistent with the mechanical passage of the coil 317 (Fig. 14).

The coil 317 (Fig. 14) can be made in any suitable fashion, and while there is illustrated in Fig. 14 a helical coil, this could be in the form of a split tube, i.e. an axially split tube constituting a substantially single turn coil, or foil sheets, i.e. a number of foil sheets wound spirally to produce a coil. Various mechanisms can be employed to transmit the motion of the coil 317 to the exterior of the housing, for example, rods parallel to the axis 312. Such construction would result in lesser flux transmittal to the exterior air, but losses through the strut slots 326, Fig 14 are within acceptable limits.

Referring to Fig. 16 there is illustrated a modification wherein the movement of the coil is transmitted to an axial rod rather than to the external periphery of the motor as in Fig. 14. A motor 340 has an external cylindrical shell 341 in which is mounted a tubular magnet 342. Washer-like end pieces 343 are disposed at each end of the shell

341, but are spaced from the ends of the magnet 342 by an appreciable gap designated by the numerals 344. A tubular magnetic core, or return circuit member, 346 is mounted in the interior diameter of the end washers 343, and has a central bore 347 within which reciprocates a rod 348, which is preferably tubular to reduce mass. The central tubular magnet member 346 has a ring-like projection 349 which is spaced from an internal sleeve 345 in intimate contact with the interior surface of the tubular magnet 342. The spacing defines an air gap 351 which is the working air gap of the motor.

Disposed within the sleeve 345 is a coil or helix 352 which, of course, has a cylindrical or tubular shape, and a portion of this helix projects into the air gap 351. The portion of the helix 352 within the air gap at any one position is the active motor part, which causes axial movement of the entire conductor helix 352. The conductor helix 352 is mechanically supported by one or more struts 354, mechanically connected to the reciprocable tube or rod 348. Suitable electrical conductors (not shown) may be passed through one or more of the struts 354 to supply electric current to the helical conductor 352. The tubular magnet core 346 is suitably slotted in a radial fashion to receive the struts 354 and allow them considerable axial movement as the coil 352 moves in response to current in it interacting with flux in the air gap 351. These slots do not appreciably weaken the magnetic return circuit.

The magnetic circuit for the motor of Fig. 16 is similar to that of Fig. 14 and for convenience an N and an S are placed on the magnet 342 of Fig. 16 to indicate a north and a south pole, respectively. In other words, the polarization of the magnet 342 is in a plane transverse to the cylindrical axis. The soft iron sleeve 345 gathers up the lines of flux from the inner surface of the magnet 342, concentrating them in the region of the pole piece 349 so that there is a high density flux in the air gap 351. The lines of flux continue through the annular pole piece 349, through the tubular magnet core 346, through the end pieces 343 and through the exterior cylindrical shell 341 to return to the opposite side of the magnet. Thus the magnetic circuit for the structure Fig. 16 is in all respects similar to that of Fig. 15.

The magnetic circuit just described forms a shell which encloses the magnet, the air gap and the pole piece so that no lines of flux can stray from the structure to interfere with nearby instruments. The interior of the bore 347 can be considered an exterior part of the shielding. Therefore, the rod 348 functions outside of the magnetic field of the motor and no appreciable flux escapes from the motor.

Various means of assembling the device of Fig. 16 could be used, including a split central core 346, preferably split lengthwise. Likewise the slots 56 could be continued to one end with little appreciable stray magnetism resulting. The magnetic return circuit is preferably of soft iron or of equivalent low reluctance, high magnetic density material. Any suitable bearings could be used for the rod 348, including bearings in the structure illustrated or external bearings of any type.

WHAT WE CLAIM IS:—

1. A linear electric motor comprising a tubular shell of magnetic material having a tubular axis; a central core of magnetic material magnetically connected to the shell by at least one low reluctance magnetic path; a tubular magnet disposed inside of the shell and having a radial polarization and defining an air gap with either the shell or the central core; a movable armature coid disposed in the air gap and having conductors generally in planes transverse to the tubular axis of the shell; means for supplying electric current to the armature coil; and means connected to the armature coil and extending to the exterior of the motor for transmitting the motion of the armature coil.

2. A linear electric motor according to claim 1, wherein an end plate of magnetic material closes off one end of the shell and is in the said magnetic path and the other end of the motor is open.

3. A linear electric motor according to claim 1, wherein end plates of magnetic material close off both ends of the shell and are in the said magnetic path.

4. A linear electric motor according to claim 1, 2 or 3, wherein a compensation winding is provided that creates a flux that opposes the flux generated by the armature coil.

5. A linear electric motor according to claim 4, wherein grooves are cut into the magnetic material forming one surface of the air gap and the said compensation winding is located in the grooves.

6. A linear electric motor according to claim 4, wherein the said compensation winding is concentrated at one part of the central core.

7. A linear electric motor according to claim 4, wherein the tubular magnet is in contact with the tubular shell and the compensation winding is on the central core.

8. A linear electric motor according to claim 4, wherein the tubular magnet is in contact with the tubular shell and the compensation winding is on the inner magnet surface.

9. A linear electric motor according to any of the preceding claims, wherein said armature coil is self-supporting and comprises a helix formed of flat anodized aluminium wire bonded together by a setting type of adhesive.

10. A linear electric motor comprising a hollow cylindrical magnet having opposite poles on the interior and exterior surfaces of the cylinder and having a cylindrical axis, means for concentrating the lines of flux located on the interior surface of the magnet; a generally cylindrical pole piece spaced from the inside surface of the magnet to define a working gap; a magnetic return circuit connecting the pole piece to the other surface of the cylindrical magnet including a low reluctance shell enclosing the magnet and the air gap; a coil disposed in the air gap for axial movement and constructed such that current can flow in it in a plane transverse to the cylinder axis; and means extending through the magnetic return circuit to mechanically transmit the motion of the coil as it moves axially within the cylindrical magnet.

11. A linear electric motor constructed and adapted to operate substantially as herein described with reference to and as illustrated by any of the embodiments shown in the accompanying drawings.

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1308349 COMPLETE SPECIFICATION

5 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

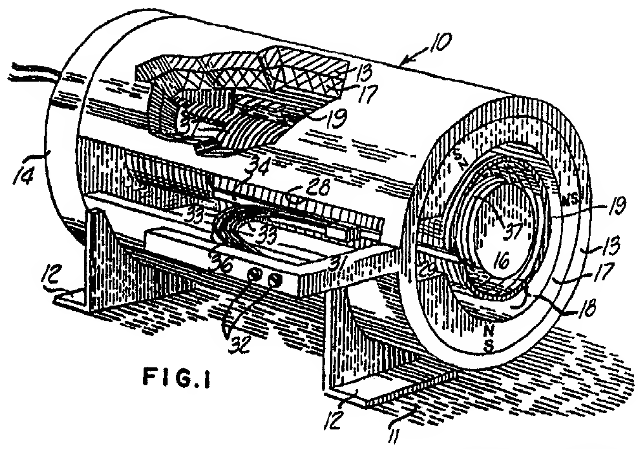

FIG. 1

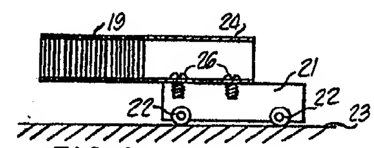

FIG. 2

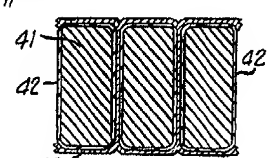

FIG. 3

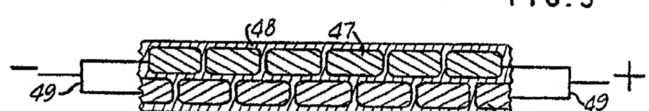

FIG. 4

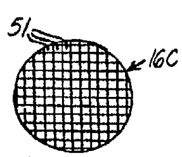

FIG. 5 MODIF.

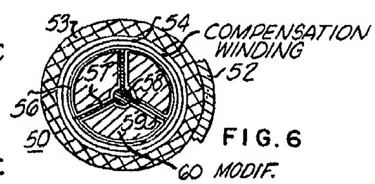

FIG. 6 MODIF.

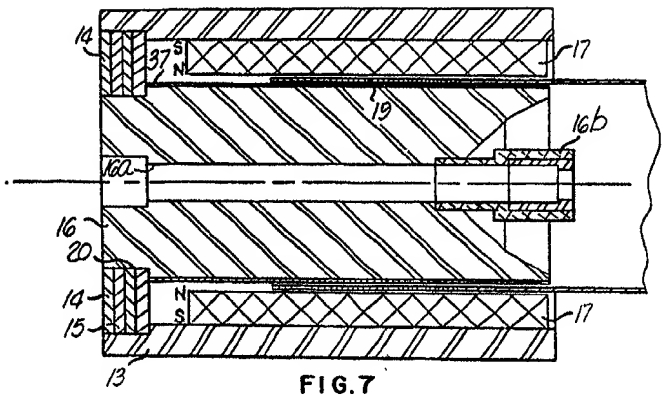

FIG.7

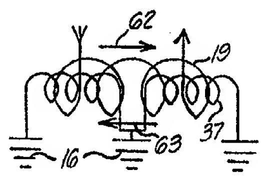

FIG.8

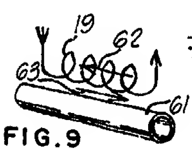

FIG.9

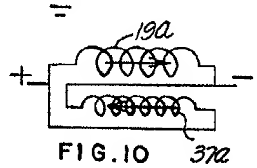

FIG.10

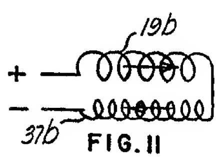

FIG.11

1308349 COMPLETE SPECIFICATION

5 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 3

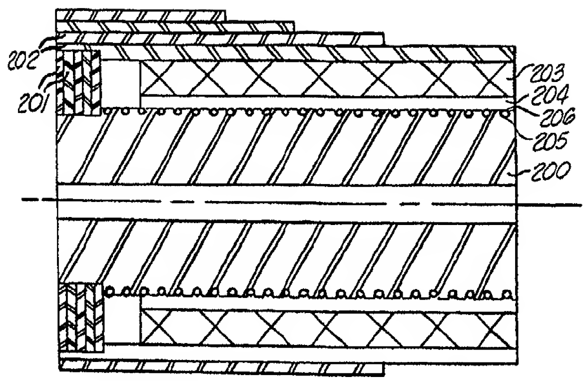

FIG. 12

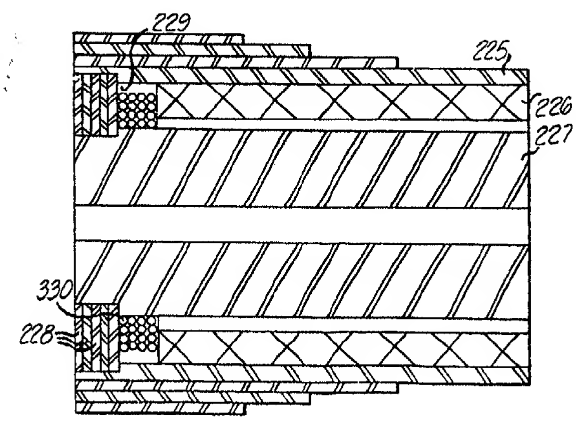

FIG. 13

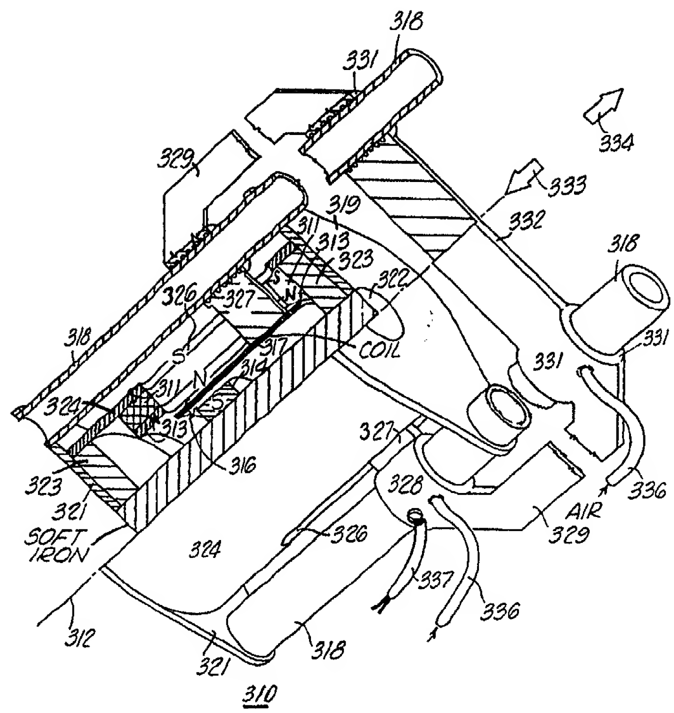
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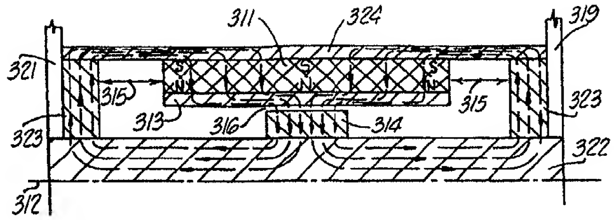
FIG.14

FIG.15



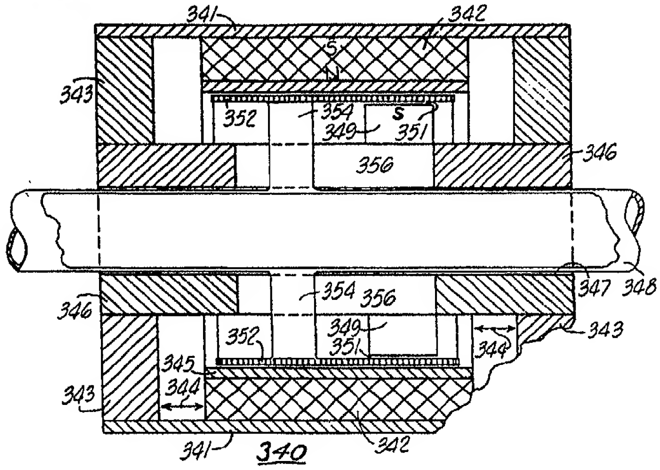


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FIG.16